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Results of preoperative pulmonary function testing of adolescents with idiopathic scoliosis: A study of six hundred and thirty-one patients

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Results of Preoperative Pulmonary Function Testing of Adolescents with Idiopathic Scoliosis

A Study of Six Hundred and Thirty-one Patients

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Background: Previous research has suggested a correlation between pulmonary impairment and thoracic spinal deformity. The curve magnitude, number of involved vertebrae, curve location, and decrease in thoracic kyphosis independently contribute to pulmonary impairment, but the strength of these associations has been variable. The objectives of this study were to test the hypothesis that increased thoracic deformity is associated with decreased pulmonary function and to determine which, if any, radiographic measurements of deformity predict pulmonary impairment.

Methods: Preoperative pulmonary function testing and radiographic examination were performed on 631 patients with adolescent idiopathic scoliosis. Correlation analysis and subsequent stepwise multiple regression analysis were carried out to assess the associations between radiographic measurements of deformity and the results of pulmonary function testing.

Results: The magnitude of the thoracic curve, the number of vertebrae involved in the thoracic curve, the thoracic hypokyphosis, and coronal imbalance had a minimal but significant effect on pulmonary function. While these four factors were associated with an increased risk of moderate or severe pulmonary impairment, they explained only 19.7%, 18.0%, and 8.8% of the observed variability in forced vital capacity, forced expiratory volume in one second, and total lung capacity, respectively. The degrees of scoliosis that were associated with clinically relevant decreases in pulmonary function were much smaller than previously described, but the majority of the observed variability in pulmonary function was not explained by the radiographic characteristics of the deformity.

Conclusions: Some patients with adolescent idiopathic scoliosis may have clinically relevant pulmonary impairment that is out of proportion with the severity of the scoliosis, and this may alter the decision-making process regarding which fusion technique will produce an acceptable clinical result with the least additional effect on pulmonary function.

There is substantial interest in the relationship between spinal deformity and pulmonary function because of the potential for increased morbidity and early mortality when pulmonary impairment is a consequence of progressive scoliosis. Recent research has revealed that surgical correction of adolescent idiopathic scoliosis can stabilize or modestly improve pulmonary function if a posterior approach is used, but additional decreases in pulmonary function may be associated with anterior fusions in which a thoracotomy is used[1-13]. Thus, both the degree of pulmonary impairment associated with the spinal deformity as well as the effect of surgical intervention are important factors in the long-term pulmonary status of the patient.

On the basis of the seminal work of Weinstein et al.[14], it has been said that there is a direct correlation between pulmonary impairment and the magnitude of the thoracic curve, with clinically relevant decreases in pulmonary function occurring only after the thoracic scoliosis has progressed beyond 100°. Other authors of studies of adolescent idiopathic scoliosis have commented on the association between pulmonary function and specific radiographic measurements of the spinal deformity[3,15-18]. Computed tomography studies paired with pulmonary function testing have suggested that the severity of the scoliosis is the most accurate predictor of lung impair-

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ment[15]. Several studies have demonstrated a negative effect of curve severity on vital capacity, with correlation coefficients ranging from –0.20 to –0.30 (a moderate effect size)[3,16,17]. Some authors have commented on the morphology of the thoracic curve, identifying the number of vertebrae in the major curve and the location of the curve as predictive factors. Others have reported on factors beyond the measurement of deformity on a standing posteroanterior radiograph and have described the negative impact of hypokyphosis and curve rigidity[16,18]. All of these studies have been based on limited numbers of patients with a range of different curve patterns.

The purpose of this study was to analyze a prospective group of 631 patients with adolescent idiopathic scoliosis to test the hypothesis that there is a correlation between increasing scoliotic deformity and decreasing pulmonary function. In addition to thoracic scoliosis, thoracolumbar and lumbar scoliotic curves were included in the study because those curve patterns, while not confined to the chest, may theoretically distort the orientation and function of the diaphragm and the mechanics of the chest with unexpected effects on pulmonary function.

Materials and Methods

Pulmonary function data on 631 patients who met the criteria for surgical intervention were prospectively collected at nine separate institutions between 1995 and 2003 as part of a multicenter prospective study of the surgical treatment of adolescent idiopathic scoliosis. Demographic data (age and gender) were recorded, and full-length posteroanterior and lateral radiographs of the spine were made with the patient standing. Several trained observers at each participating institution classified each curve according to the system of Lenke et al.[19], which incorporates the Cobb method for describing curve magnitude[20] and the King line for describing coronal balance[21]. In addition, the magnitude and flexibility of the cephalad thoracic curve, magnitude and flexibility of the main thoracic curve, number of vertebrae within the main thoracic curve, magnitude and flexibility of the lumbar curve, apex of the main thoracic curve, displacement of the apex of the main thoracic curve from a plumb line at the seventh cervical level, displacement of the seventh cervical vertebra from the central sacral vertical line, degree of thoracic kyphosis (from the second thoracic vertebra to the twelfth thoracic vertebra and from the fifth thoracic vertebra to the twelfth thoracic vertebra), and degree of lumbar lordosis were recorded and stored in a database for all patients.

All patients underwent standard pulmonary function testing prior to surgery at each participating institution. Plethysmography and pulmonary function testing were used to measure total lung capacity, forced vital capacity, and forced expiratory volume in one second. Each test was repeated three times, and the single best effort was recorded. Age, gender, and height-matched standards published by the American Thoracic Society[22] were used to generate a percentage of the predicted value for each pulmonary parameter. Unlike the radiographic measurement of deformity, standardization of pulmonary function testing protocols has not been specifically addressed by this study group, and some variability in testing at different institutions is to be expected. According to the American Thoracic Society guidelines for classifying the severity of pulmonary impairment, pulmonary function was considered to be normal when total lung capacity, forced vital capacity, and forced expiratory volume in one second were >80% of the predicted values. The patient was considered to have mild pulmonary impairment when those parameters were ≤80% but >65% of the predicted values, moderate impairment when they were ≤65% but ≥50% of the predicted values, and severe impairment when they were <50% of the predicted values[22].

Statistical Methods

The software application Statistical Package for the Social Sciences (SPSS, Chicago, Illinois) was used to conduct a correlation analysis and to determine a Pearson correlation coefficient (r) between the pulmonary parameters (percent of the predicted values for total lung capacity, forced vital capacity, and forced expiratory volume in one second) and all of the radiographic measurements of spinal deformity. The percentages of the predicted values for each of the pulmonary function parameters were used in lieu of the absolute values because these values have been controlled for age, height, and gender, thereby eliminating those factors as possible confounding variables in the analysis. Radiographic factors that had significant r values ($p < 0.01$) were entered into a stepwise multiple regression analysis, and the coefficient of multiple determination (R^2) was calculated.

In an attempt to segregate a continuous data set into categories that may have some clinical differences in pulmonary function, the previously described American Thoracic Society guidelines were used to separate the entire cohort into two groups: (1) no or mild pulmonary impairment and (2) moderate or severe pulmonary impairment. The relationship between these categories and morbidity and mortality is unknown, but the categories facilitate the process of data analysis and the stratification of the risk of pulmonary complications in association with scoliosis. The percentage of patients in each impairment group with each Lenke class of curve (1 through 6) was calculated, and a chi-square analysis was conducted on those categorical data. A chi-square analysis was also conducted to compare the degree of pulmonary impairment among hypokyphotic, normokyphotic, and hyperkyphotic patients as defined by the sagittal modifier component of the Lenke system (a sagittal Cobb angle of <10°, 10° to 40°, and >40°, respectively, from the fifth to the twelfth thoracic vertebra). A Bonferroni correction for multiple statistical tests was conducted, and significance was set at $\alpha = 0.01$.

Results

Description of Cohort

This cohort of 631 patients consisted of 532 females with a mean age (and standard deviation) of 14.5 ± 2.1 years at the time of surgical treatment and ninety-nine males with a mean age of 15.7 ± 2.1 years. In the entire cohort, the mean magnitude of the cephalad thoracic curve was 26° ± 11° (range, 0° to 83°), the mean magnitude of the main thoracic curve was 52° ± 14° (range, 2° to 110°), and the mean magnitude of the lumbar curve was 37° ± 13° (range, 8° to 93°). The thoracic kyphosis, measured from the fifth to the twelfth thoracic vertebra on the sagittal radiograph, averaged 24° ± 13° (range, –10° to 64°). The most common curve pattern was Lenke type 1 (a major thoracic curve and a minor nonstructural lumbar curve), which was found in 394 patients (62%). Lenke type 2 (double thoracic) and Lenke type 5 (thoracolumbar/lumbar) were the second and third most common curve patterns, occurring in ninety-two (15%) and seventy-nine (13%) of the patients, respectively. The remaining sixty-six patients had a Lenke type-3 (5%), 4 (3%), or 6 (3%) curve. The coronal plane deformities of the thoracic and lumbar spine and the sagittal plane measurements of kyphosis and lordosis are shown as a function of curve type in Table I.

Forced Vital Capacity

The mean absolute forced vital capacity and the percent of the predicted value for forced vital capacity in the entire cohort were 2.97 ± 0.77 L (range, 0.65 to 6.48 L) and 86% ± 17% (range, 22% to 140%), respectively. The mean percent of the predicted value fell below the American Thoracic Society threshold for normal pulmonary function (80%) once the magnitude of the main thoracic curve exceeded 70° (Table II). Correlation analysis revealed that thoracic kyphosis had a significant positive association with forced vital capacity, whereas the magnitude of the cephalad thoracic curve, magnitude of the main thoracic curve, displacement of the thoracic apex, displacement of the seventh cervical vertebra from the central sacral vertical line, degree of lumbar lordosis, and number of vertebral levels in the main thoracic curve all had negative associations with forced vital capacity (Table III). Thus, increasing thoracic scoliosis (according to these measures) and decreasing thoracic kyphosis were associated with a reduction in forced vital capacity.

These specific variables were entered into the regression analysis, which demonstrated that only the magnitude of the thoracic curve, the number of vertebrae in the thoracic curve, the degree of thoracic kyphosis, and the displacement of the seventh cervical vertebra from the central sacral vertical line were significant independent predictors of forced vital capacity. Although these variables were significant contributors, their overall contribution was minimal, as quantified by the total R^2 value of 0.197. In other words, these four factors explain only 19.7% of the variability in forced vital capacity found in this cohort. Multivariate regression analysis revealed that the deleterious effect of an increased number of levels in the thoracic curve explained 10.8% of the variability in forced

TABLE I Composition of the Study Cohort by Lenke Type and Associated Radiographic Measurements

Lenke Type	No. of Patients	Cobb Angle *(deg)* Cephalad Thoracic	Cobb Angle *(deg)* Thoracic	Cobb Angle *(deg)* Lumbar	Kyphosis *(deg)* T5 to T12	Kyphosis *(deg)* T2 to T12	Lumbar Lordosis *(deg)*
1	394	26 ± 8	52 ± 9	33 ± 9	23 ± 13	31 ± 13	–60 ± 12
2	92	40 ± 9	61 ± 13	31 ± 13	26 ± 15	34 ± 15	–60 ± 12
3	30	24 ± 7	62 ± 12	51 ± 10	28 ± 16	36 ± 16	–63 ± 12
4	16	41 ± 13	76 ± 20	58 ± 14	33 ± 14	36 ± 13	–55 ± 12
5	79	15 ± 7	47 ± 13	50 ± 10	23 ± 11	30 ± 12	–56 ± 14
6	20	19 ± 7	53 ± 6	62 ± 11	27 ± 13	34 ± 12	–54 ± 10

TABLE II Results of Pulmonary Function Tests Stratified by Magnitude of Thoracic Curve

Thoracic Curve *(deg)*	Forced Vital Capacity L	Forced Vital Capacity % of Predicted Value	Forced Expiratory Volume in 1 Sec L	Forced Expiratory Volume in 1 Sec % of Predicted Value	Total Lung Capacity L	Total Lung Capacity % of Predicted Value
≤20	3.31 ± 0.90	92 ± 15	2.84 ± 0.86	87 ± 21	4.89 ± 1.18	104 ± 14
21-30	3.45 ± 0.77	97 ± 16	2.94 ± 0.61	92 ± 14	4.50 ± 1.08	98 ± 17
31-40	3.10 ± 0.81	92 ± 16	2.66 ± 0.62	88 ± 16	4.31 ± 1.34	98 ± 20
41-50	3.01 ± 0.70	89 ± 17	2.55 ± 0.57	83 ± 17	4.07 ± 0.92	90 ± 16
51-60	3.03 ± 0.75	85 ± 16	2.57 ± 0.62	81 ± 16	4.00 ± 1.23	88 ± 20
61-70	2.79 ± 0.72	84 ± 14	2.33 ± 0.56	78 ± 13	3.71 ± 1.28	89 ± 22
71-80	2.40 ± 0.69	73 ± 18	2.01 ± 0.58	69 ± 18	3.92 ± 1.59	86 ± 22
>80	2.27 ± 0.72	69 ± 14	1.95 ± 0.56	65 ± 14	3.82 ± 0.98	83 ± 13
All	2.97 ± 0.77	86 ± 17	2.51 ± 0.64	81 ± 17	3.98 ± 1.31	90 ± 20

TABLE III Correlations Between Pulmonary Function and Radiographic Measurements of Deformity

	Correlation		
Radiographic Variable	Percent of Predicted Value for Forced Vital Capacity	Percent of Predicted Value for Forced Expiratory Volume	Percent of Predicted Value for Total Lung Capacity
Cephalad thoracic curve magnitude	–0.202*	–0.221*	–0.152*
Cephalad thoracic curve flexibility	0.040	0.041	0.027
Main thoracic curve magnitude	–0.300*	–0.293*	–0.193*
Main thoracic curve flexibility	0.025	0.027	0.031
Lumbar curve magnitude	0.058	0.045	0.093
Lumbar curve flexibility	0.009	0.012	0.026
Thoracic apex displacement	–0.117†	–0.148*	–0.186*
Thoracic apex level	–0.010	0.000	–0.070
No. of vertebrae in thoracic curve	–0.342*	–0.305*	–0.192*
C7 displacement from central sacral vertical line	–0.182*	–0.149*	–0.139†
T5 to T12 kyphosis	0.157*	0.174*	0.153*
T2 to T12 kyphosis	0.230*	0.242*	0.211*
Lumbar lordosis	–0.100*	–0.127*	–0.076

*P < 0.002. †P < 0.01.

vital capacity, reduced kyphosis explained 4.3%, the magnitude of the thoracic curve explained 3.6%, and coronal imbalance explained 1.0% (Table IV). The remaining 80.3% of the relationship between adolescent idiopathic scoliosis and forced vital capacity remained undetermined.

Forced Expiratory Volume in One Second

Similar results were obtained in the analysis of forced expiratory volume in one second, which was 2.51 ± 0.64 L (range, 0.65 to 5.48 L) in the entire cohort, or 81% ± 17% (range, 25% to 134%) of the predicted value. The percent of the predicted value fell below the American Thoracic Society threshold of normal pulmonary function (80%) once the magnitude of the main thoracic curve exceeded 60° (Table II). The correlation analysis revealed a pattern of associations with radiographic factors that was similar to that found with forced vital capacity. As the magnitudes of the cephalad thoracic and main thoracic curves increased, the forced expiratory volume in one second decreased. Likewise, more deviation in the thoracic apex, a longer main thoracic curve, and increased coronal imbalance were all associated with a decreased forced expiratory volume in one second. Increased thoracic kyphosis and lumbar lordosis were both correlated with increased forced expiratory volume in one second (Table III). However, the regression analysis revealed that, as was found in the analysis of forced vital capacity, only four of these factors had significant independent effects on the variability in forced expiratory volume in one second (Table IV). The number of vertebra in the thoracic curve made the most significant contribution, accounting for 8.6% of the variability in forced expiratory volume in one second. The magnitude of the thoracic curve and the thoracic kyphosis accounted for 4.7% and 4.1% of the variability, respectively. Coronal imbalance, as measured by the displacement of the seventh cervical vertebra from the central sacral vertical line, accounted for <1% of the variability. Again, radiographic signs of deformity explained

TABLE IV Radiographic Markers Significantly and Independently Contributing to Variability in Pulmonary Function

	Coefficient of Multiple Determination (R^2)		
	Percent of Predicted Value for Forced Vital Capacity	Percent of Predicted Value for Forced Expiratory Volume (%)	Percent of Predicted Value for Total Lung Capacity
No. of vertebrae in thoracic curve	0.108	0.086	—
Thoracic curve magnitude	0.036	0.047	0.036
T2 to T12 kyphosis	0.043	0.041	0.038
C7 displacement from central sacral vertical line	0.010	0.006	—
Thoracic apex displacement	—	—	0.014
Total	0.197	0.180	0.088

only a total of 18% of the variability in forced expiratory volume in one second.

Total Lung Capacity

The mean total lung capacity and percent of the expected value for total lung capacity in the entire cohort were 4.06 ± 1.19 L (range, 1.04 to 10.10 L) and 90% ± 19% (range, 49% to 196%). These values decreased with increasing curve size, as shown in Table II. However, even when the thoracic curve exceeded 80°, the mean percent of the predicted value for total lung capacity remained above the American Thoracic Society threshold for normal pulmonary function. The pattern of cor-

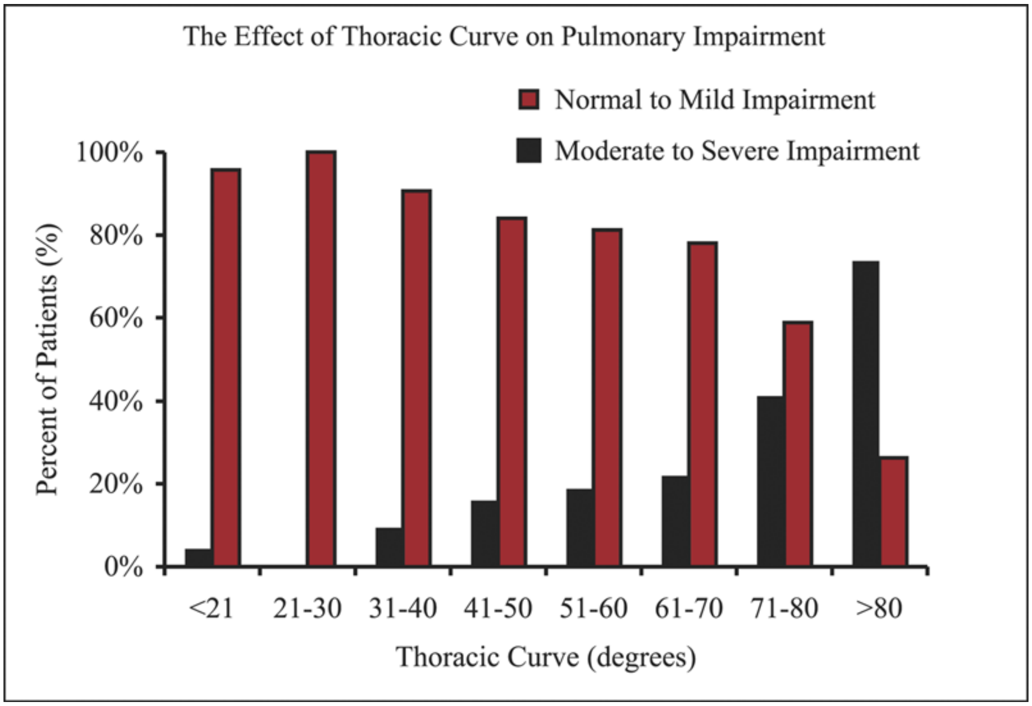

Fig. 1

Bar graph illustrating that increased coronal deformity is associated with increased pulmonary impairment.

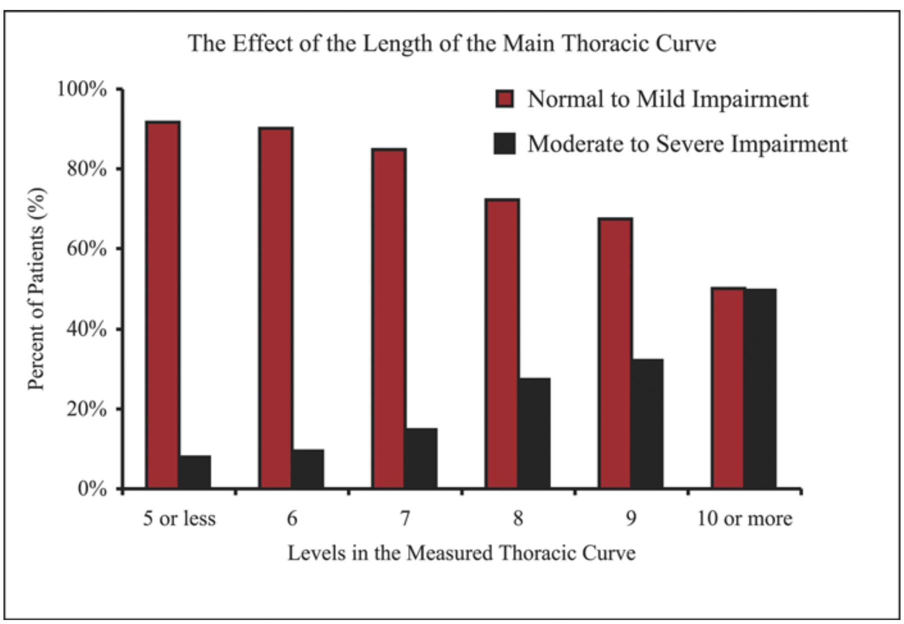

Fig. 2

Bar graph depicting the correlation between increased length of the thoracic curve (number of vertebrae over which the thoracic Cobb angle is measured) and pulmonary impairment.

relations with radiographic factors was similar to those found for the other measures of pulmonary function (Table III). However, the regression analysis revealed that the most influential radiographic factors were thoracic curve magnitude and thoracic kyphosis ($R^2 = 0.036$ and 0.038). Displacement of the thoracic apex made a small contribution to the equation. The length of the thoracic curve made no independent contribution to the regression equation.

Thoracic Curve Morphology

When the cohort was stratified into two groups—i.e., normal or mild pulmonary impairment and moderate or severe pulmonary impairment—we found an increasing percentage of abnormal results with increasing curve magnitude and increasing curve length, an observation supported by the findings in the correlation and regression analyses ($p < 0.001$) (Figs. 1 and 2). Fifty-four (20%) of 273 patients with a thoracic curve of 50° to 70° had moderate or severe pulmonary impairment, whereas fourteen (41%) of thirty-four patients with a thoracic curve of 71° to 80° had one or more pulmonary function test results that were <65% of the predicted value. Although only nineteen patients in the study cohort had a thoracic curve of ≥80°, fourteen (74%) of them had moderate or severe pulmonary impairment. A similar pattern was seen for the length of the thoracic curve. Only fifty (13%) of 391 patients with a thoracic curve involving seven or fewer vertebral levels had moderate or severe pulmonary impairment; however, seventy-one (30%) of 240 patients with eight or more levels in the thoracic curve had moderate or severe impairment.

Thoracic Kyphosis

Eighty-three (13%) of the 631 patients had hypokyphosis according to the definition in the classification system of Lenke et al.[19] (≤10° between the fifth and twelfth thoracic vertebrae), and they were more likely than the other patients in the cohort to have moderate or severe pulmonary impairment (Fig. 3). The correlation and regression analyses revealed that the thoracic sagittal plane deformity was an important radiographic factor, with an R^2 value that ranged from 0.040 to 0.043. Twenty-four (29%) of the eighty-three patients with hypokyphosis had moderate or severe pulmonary impairment as compared with ninety-one (19%) of 479 patients with normal kyphosis (10° to 40°) and seven (10%) of sixty-nine patients with hyperkyphosis. Additional chi-square analysis revealed a significant difference in pulmonary impairment between the patients with hypokyphosis and those with hyperkyphosis ($p = 0.01$) but no significant difference between either group and the patients with normal kyphosis.

Lenke Classification

The relationship between the Lenke curve type and the degree of pulmonary impairment was assessed with chi-square analysis. The prevalences of pulmonary impairment were highest in patients with type-1, 2, and 4 curves (Fig. 4). Of the ninety-two patients with a Lenke type-2 pattern (double thoracic),

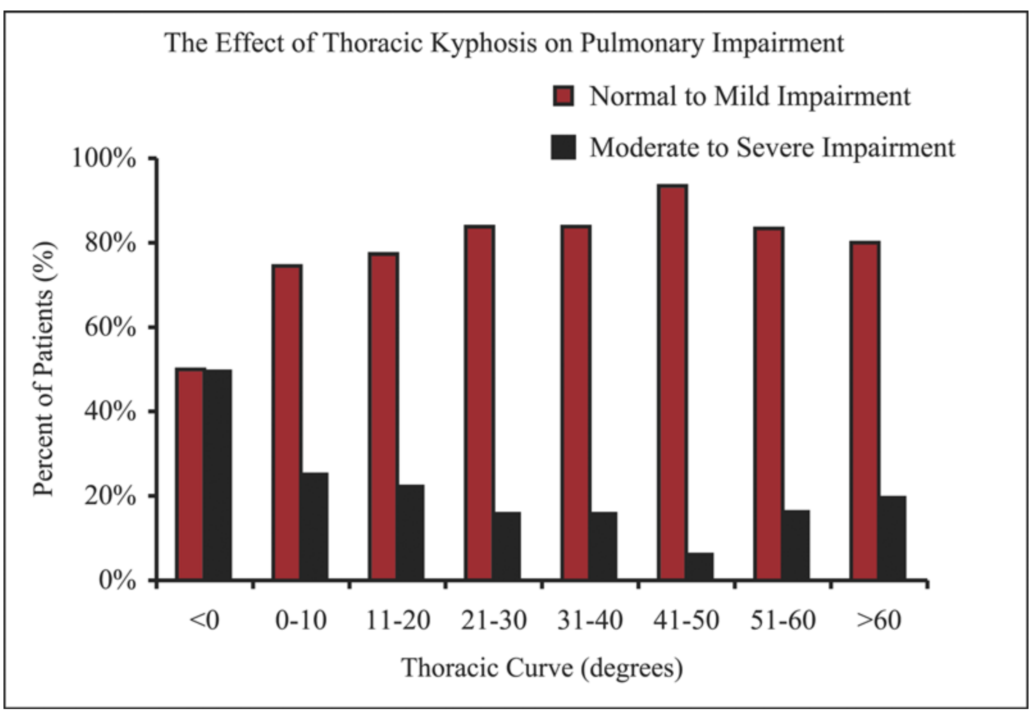

Fig. 3

Bar graph demonstrating the effect of the sagittal plane deformity (as measured by the Cobb angle from the fifth to the twelfth thoracic vertebra) on pulmonary function. The prevalence of moderate or severe pulmonary impairment is significantly higher ($p \le 0.01$) in patients with thoracic hypokyphosis of ≤10°.

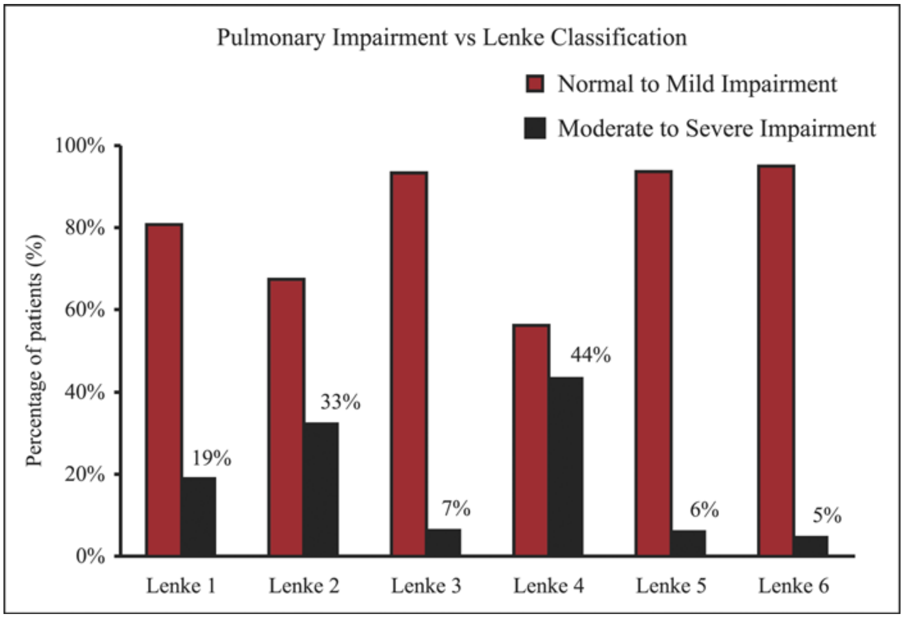

Fig. 4

Bar graph demonstrating the prevalence of moderate or severe pulmonary impairment for each Lenke curve type in the study cohort. Primary thoracic curves were associated with impaired pulmonary function, whereas patients in whom the primary curve was lumbar or thoracolumbar were less likely to have moderate or severe impairment.

thirty (33%) had moderate or severe pulmonary impairment. Only sixteen patients in this large cohort had a Lenke type-4 (triple thoracic) curve pattern; however, seven (44%) of them had moderate or severe pulmonary impairment. The prevalence of moderate or severe impairment was smaller in the group with a Lenke type-1 curve (seventy-six [19%] of 394 patients). The patterns with a major thoracolumbar/lumbar curve were associated with lower prevalences of moderate or severe impairment, which was found in two (7%) of thirty patients with a Lenke type-3 curve, five (6%) of seventy-nine with a Lenke type-5 curve, and one (5%) of twenty with a Lenke type-6 curve. Chi-square analysis revealed a significant difference in the prevalence of pulmonary impairment across all Lenke types ($p < 0.001$).

Discussion

The relationship between spinal deformity and pulmonary function has been the subject of a large number of clinical studies, which have addressed the association between scoliosis and the prevalence of abnormal results of pulmonary function testing, shortness of breath, and morbidity and mortality as a result of pulmonary impairment[7,11,12,14,15,17,18,23-25]. The effect of chest-wall mobility, exercise, orthoses, correction of the spinal deformity, thoracoplasty, and surgical technique on thoracic volume and pulmonary function values have also been investigated[3,14-18,23].

The present study was designed to test the hypothesis that increasing thoracic scoliosis is associated with decreasing pulmonary function in patients with adolescent idiopathic scoliosis when compared with age, sex, and height-matched controls. This hypothesis was found to be true in our study of 631 patients, and two additional radiographic features, the length of the thoracic curve and hypokyphosis, also had significant but weak correlations with pulmonary function.

The variability of the accuracy of pulmonary function testing is well known and a limitation of this study[26]. There are also theoretical concerns about using normative data based on height and gender to derive predicted values for pulmonary function test data in an evaluation of a condition that affects the measurement of the height of the test subject[26,27]. The results of the pulmonary function tests were not corrected for the reduction in height due to the scoliosis. This may have led to a slight underestimation of the reduction in pulmonary function associated with scoliosis, as this cohort was compared with normal subjects who were shorter than the scoliotic patients would have been if they had not lost height as a result of the spinal curvature. Additional common comorbidities, such as restrictive airway disease, can affect the measurement of pulmonary function in this population and may be a confounding variable. Also, patients with scoliosis may be less active and participate less in sports and exercise than their age and sex-matched peers, and this may have an effect on their apparent pulmonary function.

Our results partially confirm the findings of several earlier studies, but they raise additional questions about the relationship between spinal deformity and pulmonary function[7,11,12,14,15,17,18,23-25]. The occurrence of moderate or severe pulmonary impairment in association with thoracic scoliotic curves of <50° contradicts the widely held assumption that only severe scoliosis is associated with pulmonary impairment[14]. In a thirty-year follow-up study of 219 patients with untreated idiopathic scoliosis, Weinstein et al.[14] concluded that, in the natural history of adolescent idiopathic scoliosis, pulmonary function is not significantly impaired until the thoracic curve reaches 100° to 120°.

The findings of the present study suggest that pulmonary function deficits occur in a substantial proportion of patients with much smaller curves. Although there was a significant trend toward an increasing prevalence of impairment with increasing thoracic curvature, a plot depicting the sagittal and coronal deformities of patients with normal or mildly impaired pulmonary function versus those with moderate or severe impairment revealed a disturbing lack of a clear threshold of deformity associated with pulmonary impairment (Fig. 5). Since all of these patients were candidates for surgical treatment, it can be assumed that patients with a structural thoracic curve would not be selected for surgery (and therefore receive pulmonary function testing) unless they had ≥40° of coronal plane deformity. In Figure 5, the subjects with a thoracic curve of <40° are those in whom the major curve was thoracolumbar or lumbar. It is possible that major thoracic curves affect pulmonary function differently than do compensatory thoracic curves, by distorting the orientation and function of the diaphragm or the mechanics of the chest cage.

Several clinical studies have supported the concept that spinal deformity, as evidenced on radiographs, influences pulmonary function in patients with adolescent idiopathic scoliosis. Aaro and Ohlund[15] conducted computed tomography studies of the chest cage in thirty-three patients with adolescent idiopathic scoliosis and reported reduced lung volumes, with coronal deformity having a stronger restrictive effect on pulmonary function than sagittal deformity. Jackson et al.[16] further substantiated these trends with a pulmonary function study of forty-one adults with untreated adolescent-onset idiopathic scoliosis; they concluded that forced vital capacity was significantly impaired ($p < 0.008$) in patients with scoliosis of >40°. Kearon et al. drew similar conclusions in their study of sixty-six patients with adolescent idiopathic scoliosis, although they acknowledged that the severity of the scoliosis alone was not adequate to predict clinical pulmonary dysfunction[18]. In a clinical study of seventy patients with right thoracic adolescent idiopathic scoliosis, Upadhyay et al. also concluded that there was a negative correlation between curve magnitude and vital capacity[17].

Spinal inflexibility has been addressed as a potential factor contributing to pulmonary dysfunction in several studies. On the basis of an analysis of the recumbent side-bending radiographs and pulmonary function values of forty-one patients, Jackson et al. concluded that increased curve rigidity was correlated with increased pulmonary impairment[16]. Conversely, Upadhyay et al. examined the side-bending radiographs and pulmonary function test results of seventy patients with adolescent idiopathic scoliosis and concluded that there was no correlation between curve flexibility and pulmonary function[17]. Leong et al. used motion analysis studies to compare the kinematics of the chest cage in patients with adoles-

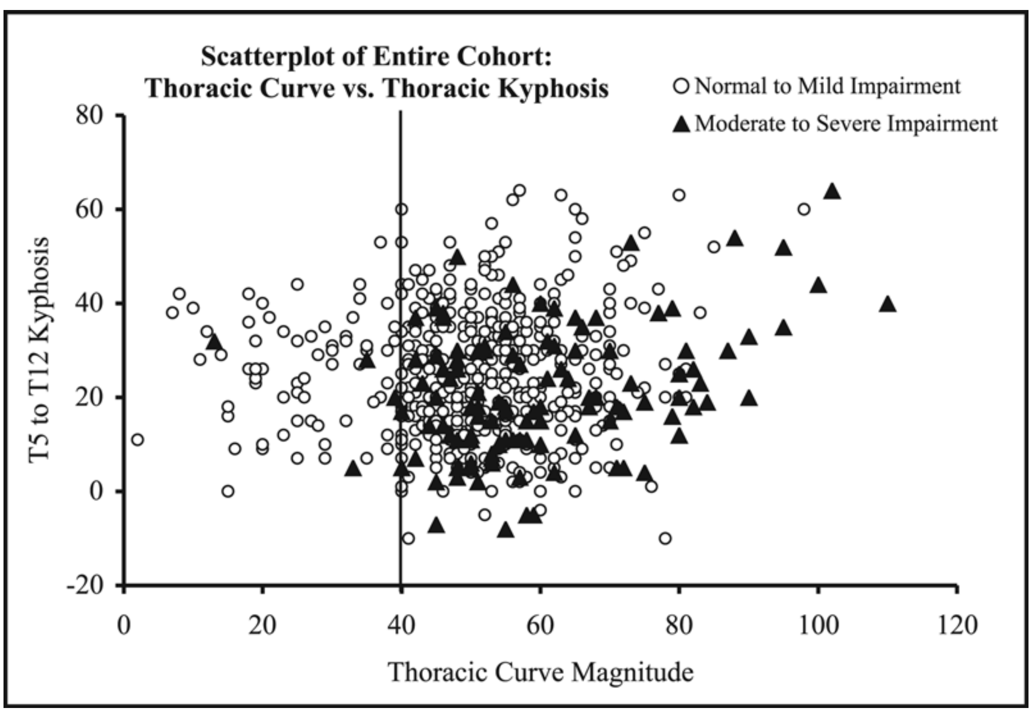

Fig. 5

Scatterplot depicting the distribution of patients with moderate or severe impairment with respect to thoracic curve magnitude and kyphosis. The vertical line indicates that patients were not considered to be potential surgical candidates or referred for pulmonary function testing until the coronal thoracic deformity measured ≥40°.

cent idiopathic scoliosis that had not been surgically corrected with those in normal volunteers[23]. They concluded that increased spinal rigidity in patients with scoliosis impaired chest excursion and therefore pulmonary function. In the present study, we found no correlation between curve flexibility and any of the measurements of pulmonary function (Table III). Although the belief that curve rigidity affects chest excursion is logical and supported by the work of Leong et al.[23], the analysis of our large cohort revealed that it was not a significant contributor to pulmonary dysfunction.

Upadhyay et al. found that thoracic kyphosis had a significant effect on static lung volumes such as residual volume ($p = 0.046$), total lung capacity ($p = 0.022$), and functional residual capacity ($p = 0.036$) but did not have a significant effect on forced vital capacity or forced expiratory volume in one second[17]. Kearon et al. concluded that the loss of normal thoracic kyphosis was a significant factor ($p = 0.002$) contributing to pulmonary impairment[18]. In contrast, Jackson et al. drew no conclusions about the effects of hypokyphosis but stated that thoracic hyperkyphosis (>50°) was related to decreased pulmonary function[16]. In the current study, there was a positive correlation between thoracic kyphosis and pulmonary function. Patients with hypokyphosis of ≤10° were more likely to have pulmonary impairment, whereas thoracic hyperkyphosis of ≥41° was associated with improved pulmonary function.

The present study addressed other issues raised in the study by Kearon et al.[18], who concluded that an increased number of vertebrae in the thoracic curve ($p = 0.007$) and a more cephalad location of the curve ($p = 0.04$) were both significant contributors to pulmonary dysfunction. In the current analysis, there was no correlation between the location of the thoracic apex and any measurement of pulmonary function. However, the number of vertebrae in the thoracic curve was the most significant predictor of both forced vital capacity and forced expiratory volume in one second. This finding may be related to vertebral rotation and overall three-dimensional changes in the chest cavity that are difficult to quantify by two-dimensional means. Several studies have demonstrated a close association between vertebral rotation and pulmonary dysfunction; however, the reliability of measurements of vertebral rotation is low, casting suspicion on any subsequent conclusions[16,17]. Analysis utilizing a more reliable method of measuring vertebral rotation or three-dimensional imaging such as computed tomography may elucidate the relationship between spinal deformity and pulmonary dysfunction. We believe that future developments in imaging technology may allow us to better assess the effects of scoliosis on thoracic shape and may provide new insights into the relationship between spinal deformity and pulmonary function.

The analysis of the severity of pulmonary impairment stratified by Lenke curve type also revealed some important trends. Lenke type-2 and 4 patterns, both of which consist of structural cephalad and main thoracic curves, were associated with the highest prevalences of moderate or severe impairment (33% and 44%, respectively). The presence of two relatively inflexible curves within the thoracic spine must adversely affect chest kinematics and lung function.

Recent research has revealed that surgical correction of adolescent idiopathic scoliosis may stop the decline in pulmonary function that is expected with curve progression. Correction of the deformity through the posterior approach may be associated with modest improvement in pulmonary function, whereas anterior spinal fusion through an open thoracotomy approach may actually be associated with additional declines in pulmonary function[1,4,6,7,11,12,28]. The comparative effects of thoracoscopic fusions are a subject of several ongoing studies, but preliminary results suggest that these procedures do not significantly worsen or improve pulmonary function[2,10]. Therefore, the awareness that some patients with moderate-sized curves may have substantial pulmonary impairment may assist with the selection of the appropriate surgical technique for correction. We believe that pulmonary function testing is useful, but not essential, in the preoperative evaluation of patients with adolescent idiopathic scoliosis.

Although this analysis revealed radiographic factors that have a significant effect on pulmonary function, that effect was small. These data suggest that patients with a structural cephalad thoracic curve, a major thoracic curve spanning eight or more vertebral levels, or thoracic hypokyphosis are at increased risk for moderate or severe pulmonary impairment. However, these factors explain only 20.1% of the observed variability in the results of pulmonary function testing. Therefore, we suggest that the treating surgeon may wish to consider preoperative pulmonary function testing when faced with these radiographic criteria and when contemplating a surgical approach that may have deleterious effects on pulmonary function, such as a thoracotomy.

The lack of any moderate or strong effect-size correlations between radiographic measurements of deformity and the results of pulmonary function testing demonstrates that it is difficult to quantify global thoracic deformity with current two-dimensional measurement techniques. Additional research on the three-dimensional nature of spinal and thoracic deformities and improved techniques for measuring pulmonary impairment will be instrumental in increasing our understanding of how scoliosis has a deleterious effect on thoracic shape and function. Longer-term follow-up of this cohort will also help to elucidate the appropriate indications for open anterior, posterior, and thoracoscopic fusion with respect to their additive effects on perioperative pulmonary impairment after surgical correction of scoliosis. ■

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